# Precision Frontier: Status and Future of Electroweak Precision Observables

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# Precision physics with $W$ and $Z$ bosons

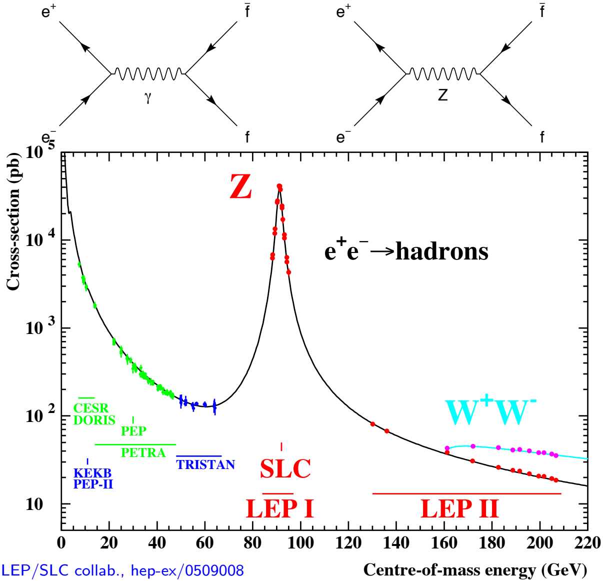
$W$ and $Z$ production processes are one of the theoretically best understood, most precise experimental probes of the Standard Model (SM):

- Test of the SM as a fully-fledged Quantum Field Theory: sensitivity to multi-loop and non-universal radiative corrections.
- Check of the consistency of the SM by comparing direct with indirect measurements of model parameters, e.g., $m_{top}, M_W, \sin^2\theta^l_{eff}, M_H$.
- Search for indirect signals of Beyond-the-SM (BSM) physics in form of small deviations from SM predictions, yielding exclusions of, and constraints on, BSM scenario complementary to direct searches for new particles.

Multi-electroweak gauge boson processes:

- Electroweak (EW) gauge boson pair and triple production directly probes the non-abelian gauge structure of the SM.
- Vector boson fusion processes, e.g. $WW \to WW$ scattering, directly probe the EWSB sector of the SM.
- Search for non-standard gauge boson interactions provide an unique indirect way to look for signals of new physics in a model-independent way.
- Improved constraints on anomalous triple-gauge boson couplings (TGCs) and quartic couplings (QGCs) can probe scales of new physics in the multi-TeV range.

# Electroweak precision physics requires high-precision measurements




LEP/SLC collab., hep-ex/0509008

# Electroweak precision physics requires excellent control of predictions at the quantum-loop level

Predictions for cross sections ($d\sigma$) and asymmetries are based on perturbation theory, i.e. an expansion in the interaction Lagrangian, which results into an expansion of the amplitude in orders of the coupling strength $g$:

$$\mathcal{M}(g) = g^k \mathcal{A}^0 + g^{k+1}\mathcal{A}^1 + g^{k+2}\mathcal{A}^2 + \ldots$$

Lowest order (LO): $\mathcal{A}^0$ describes the desired final state with minimum extra radiation and a minimal number of interactions:

$$e^+e^- \to f\bar{f} : d\sigma_{\mathrm{LO}}(q^2, \alpha, m_f, m_e, M_Z) \text{ is } \text{ of } \mathcal{O}(\alpha^2)$$

Radiative corrections are contributions beyond LO describing the real radiation of one, two, ... extra particles and the virtual presence of particles in quantum loops.
Fixed order (NLO, NNLO ...):

$$d\sigma_{NLO,NNLO} \propto g^{2k}|\mathcal{A}^0|^2 + g^{2(k+1)}|\mathcal{A}^1|^2 + 2g^{k+2+k}\mathcal{R}e(\mathcal{A}^2\mathcal{A}^{0*}) + \ldots$$

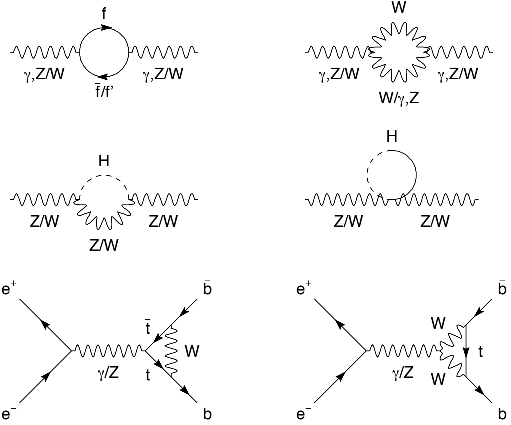
Beyond fixed order: resummation of logarithmic enhanced corrections ($L = \ln(A), \alpha = g^2$)

$$1 + \alpha(L^2 + L + 1) + \alpha^2(L^4 + L^3 + L^2 + L + 1) + \ldots \to$$

$$C(\alpha)\exp\left[Lg_1(\alpha L) + g_2(\alpha L) + \alpha g_3(\alpha L) + \ldots\right] + R(\alpha)$$

# Electroweak precision physics: $e^+e^- \to f\bar{f}$ at NLO EW

At NLO EW $\sigma_{\mathrm{NLO}}(q^2, \alpha, m_f, m_e, M_Z, m_{top}, M_H, \ldots)$ is of $\mathcal{O}(\alpha^3)$ and includes weak 1-loop corrections, which modify $Zf\bar{f}$ couplings and the $Z$ propagator as follows:



# EW (Pseudo-)Observables around the Z resonance

Taken from D.Bardin *et al.*, hep-ph/9902452

Pseudo-observables are extracted from "real" observables (cross sections, asymmetries) by de-convoluting them of QED and QCD radiation and by neglecting terms ($\mathcal{O}(\alpha\Gamma_Z/M_Z)$) that would spoil factorization ($\gamma, Z$ interference, $t$-dependent radiative corrections).

The $Zf\bar{f}$ vertex is parametrized as $\gamma_\mu(G_V^f + G_A^f\gamma_5)$ with formfactors $G_{V,A}^f$, so that the partial Z width reads:

$$\Gamma_f = 4N_c^f\Gamma_0(|G_V^f|^2 R_V^f + |G_A^f|^2 R_A^f) + \Delta_{EW/QCD}$$

$R_{V,A}^f$ describe QED, QCD radiation and $\Delta$ non-factorizable radiative corrections.

Pseudo-observables are then defined as ($g_{V,A}^f = ReG_{V,A}^f$)

- $\sigma_h^0 = 12\pi\frac{\Gamma_e\Gamma_h}{M_Z^2\Gamma_Z^2}$ , $R_{q,l} = \Gamma_{q,h}/\Gamma_{h,l}$
- $A_{FB}^f = \frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B} \to A_{FB}^{f,0} = \frac{3}{4}A_e A_f, A_f = 2\frac{g_V^f g_A^f}{(g_V^f)^2+(g_A^f)^2}$
- $A_{LR}(SLD) = \frac{N_L-N_R}{N_L+N_R}\frac{1}{<P_e>} \to A_{LR}^0(SLD) = A_e$

and $4|Q_f|\sin^2\theta_{eff}^f = 1 - \frac{g_V^f}{g_A^f}$ with $g_{V,A}^f$ being *effective* couplings including radiative corrections.

# EWPOs around the Z resonance

To match or beter exceed the experimental accuracy, EWPOs had to be calculated beyond NLO, some up to leading 4-loop corrections, but complete NNLO EW for all EWPOs is not available.
Some of the most important precision observables for $Z$-boson production and decay and their present-day and future estimated theory errors: (see discussion by A.Freitas in EW WG Snowmass report)

| Quantity | Current theory error | Leading missing terms | Est. future theory error |
|---|---|---|---|
| $\sin^2\theta^l_{\text{eff}}$ | $4.5\times10^{-5}$ | $\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq2}\alpha^3)$ | $1...1.5\times10^{-5}$ |
| $R_b$ | $\sim 2\times10^{-4}$ | $\mathcal{O}(\alpha^2)$, $\mathcal{O}(N_f^{\geq2}\alpha^3)$ | $\sim 1\times10^{-4}$ |
| $\Gamma_Z$ | few MeV | $\mathcal{O}(\alpha^2)$, $\mathcal{O}(N_f^{\geq2}\alpha^3)$ | $< 1$ MeV |

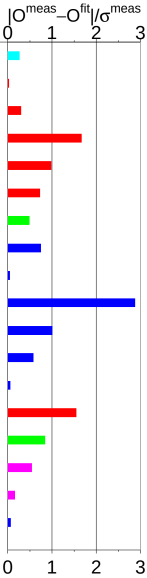
Precise predictions for EWPOs for global fits are provided for instance by the LEPEWWG based on the Monte Carlo programs ZFITTER by Bardin et al., using the following set of input parameters:

$$\Delta\alpha^{(5)}_{had}, \alpha_s(M_Z), M_Z, m_t, M_H, G_\mu$$

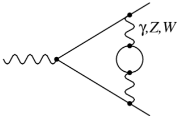
and GFITTER, J.Erler *et al* PDG 2012, Ciuchini *et al.*, 1306.4644.

# EWPO: Measurements vs SM Predictions

| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | $0.02750 \pm 0.00033$ | 0.02759 |
| $m_Z$ [GeV] | $91.1875 \pm 0.0021$ | 91.1874 |
| $\Gamma_Z$ [GeV] | $2.4952 \pm 0.0023$ | 2.4959 |
| $\sigma_{had}^{0}$ [nb] | $41.540 \pm 0.037$ | 41.478 |
| $R_l$ | $20.767 \pm 0.025$ | 20.742 |
| $A_{fb}^{0,l}$ | $0.01714 \pm 0.00095$ | 0.01645 |
| $A_l(P_\tau)$ | $0.1465 \pm 0.0032$ | 0.1481 |
| $R_b$ | $0.21629 \pm 0.00066$ | 0.21579 |
| $R_c$ | $0.1721 \pm 0.0030$ | 0.1723 |
| $A_{fb}^{0,b}$ | $0.0992 \pm 0.0016$ | 0.1038 |
| $A_{fb}^{0,c}$ | $0.0707 \pm 0.0035$ | 0.0742 |
| $A_b$ | $0.923 \pm 0.020$ | 0.935 |
| $A_c$ | $0.670 \pm 0.027$ | 0.668 |
| $A_l$(SLD) | $0.1513 \pm 0.0021$ | 0.1481 |
| $\sin^2\theta_{eff}^{lept}(Q_{fb})$ | $0.2324 \pm 0.0012$ | 0.2314 |
| $m_W$ [GeV] | $80.385 \pm 0.015$ | 80.377 |
| $\Gamma_W$ [GeV] | $2.085 \pm 0.042$ | 2.092 |
| $m_t$ [GeV] | $173.20 \pm 0.90$ | 173.26 |




March 2012




New: ferm. 2-loop corr. reduce $R_b$ by approx exp. error

Freitas, Huang, 1205.0299

LEPEWWG, March 2012

SM predictions for the

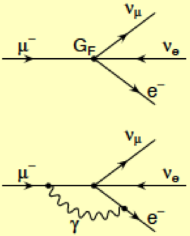
Z pole EWPOs predicted by ZFITTER

Bardin et al (1999)

# Predicting the W boson mass

Muon decay is well-approximated by effective
4-fermion interaction in the limit $q^2 << M_W^2$ from talk by A.Freitas at Seattle Snowmass EF meeting:

## $\mu$ decay in Fermi Model

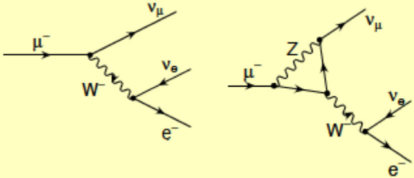



← QED corr. (2-loop)

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3} F\left(\frac{m_e^2}{m_\mu^2}\right)(1+\Delta q)$$

Ritbergen, Stuart '98

## $\mu$ decay in Standard Model




$$\frac{G_F^2}{\sqrt{2}} = \frac{e^2}{8 s_W^2 M_W^2}(1+\Delta r)$$

electroweak corrections

# Predicting the W boson mass

Implicit equation for $M_W$:

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha(0)}{2s_w^2 M_W^2}[1 + \Delta r(\alpha, M_W, M_Z, m_t, M_H, \ldots)]$$

$\Delta r$ describes the loop corrections to muon decay:

$$\Delta r = \Delta\alpha - \frac{c_w^2}{s_w^2}\Delta\rho(0) + 2\Delta_1 + \frac{s_w^2 - c_W^2}{s_w^2}\Delta_2 + \text{boxes, vertices, higher orders}$$

$\Delta\rho(0)$ at 1-loop is given in terms of 1-PI EW gauge boson self energies, $\Pi^T_{V_1 V_2}$:

$$\Delta\rho(0) = \frac{\Pi^T_{WW}(0)}{M_W^2} - \frac{\Pi^T_{ZZ}(0)}{M_Z^2} - 2\frac{s_W}{c_W}\frac{\Pi^T_{Z\gamma}(0)}{M_Z^2}$$

$\Delta\alpha$ describes contributions to the running of $\alpha$: $\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{top} + \Delta\alpha^{(5)}_{had} + \ldots$

# Parametric and theory uncertainties in $M_W$

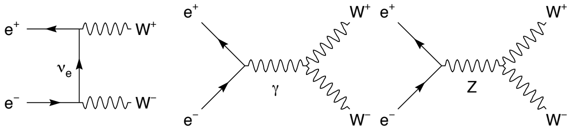
Theory uncertainty are due to missing 3-loop corrections of $\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$.
Parametric uncertainties (Awramik *et al*, EW WG Snowmass report):

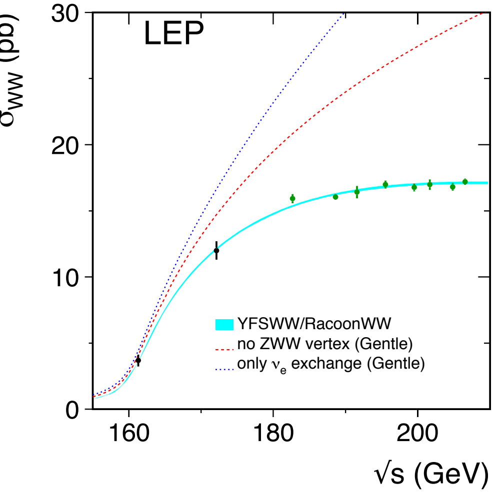
$$M_W = M_W^0 - c_1 \ln\left(\frac{M_H}{100\text{GeV}}\right) + c_6 \left(\frac{m_t}{174.3\text{GeV}}\right)^2 - 1 + \ldots$$

| $\Delta M_W$ [MeV] | present | future |
|---|---|---|
| $\Delta m_t = 0.9; 0.6(0.1)$ GeV | 5.4 | 3.6(0.6) |
| $\Delta(\Delta\alpha_{\rm had}) = 1.38(1.0); 0.5 \cdot 10^{-4}$ | 2.5(1.8) | 1.0 |
| $\Delta M_Z = 2.1$ MeV | 2.6 | 2.6 |
| missing h.o. | 4.0 | 1.0 |
| total | 7.6(7.4) | 4.7(3.0) |

See discussion by Ayres Freitas in Snowmass EW WG report.

# $M_W$ measurement at LEP2




$\Delta M_W = 33$ MeV

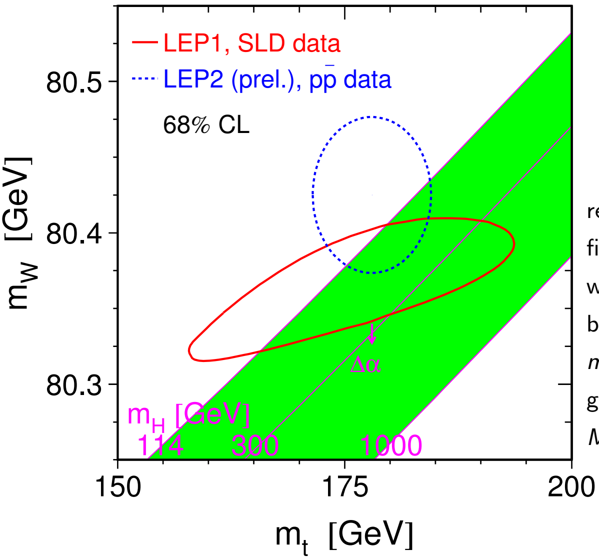
Best prediction includes NLO EW to $e^+e^-$ -

and dominant NNLO corr. at threshold.

Theory uncert. due to missing NNLO corr.:

$\Delta M_W \approx 3$ MeV at threshold

see discussion by C.Schwinn in Snowmass EW WG report




red ellipse:

fit of SM pred. to EWPOs

with $M_W$, $m_{top}$ free

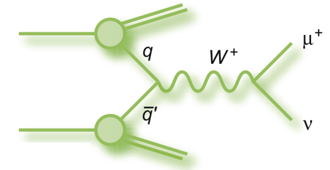
blue ellipse:

$m_{top}$, $M_W$ measurement

green band:

$M_W(m_{top}, M_H)$ SM prediction

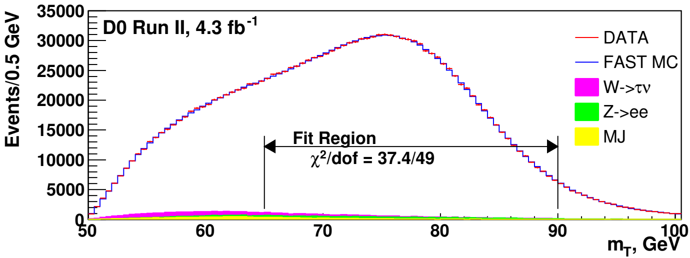
LEPEWWG 2005



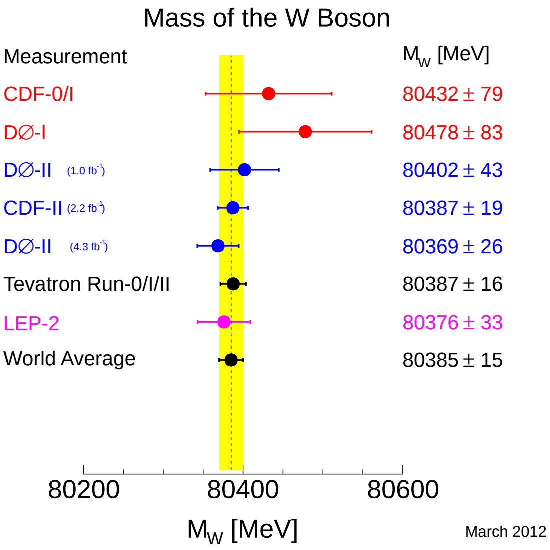

$M_W$ from the transverse mass of the $l\nu$ pair in $p\bar{p} \to W \to l\nu$:

$\delta M_W = 16$ MeV with 7.6 $fb^{-1}$

TEVEWWG, arXiv:1204.0042



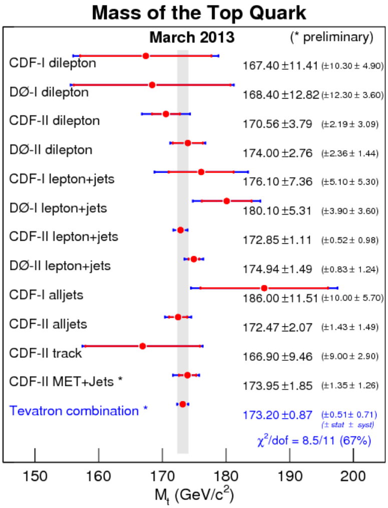
# A new era of EW precision physics - $\delta M_W^{exp} \approx 0.02\%$




LEPEWWG March 2012

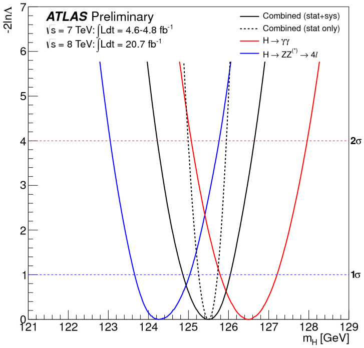
## A new era of EW precision physics: $\delta m_{top}^{exp} \approx 0.54\%$

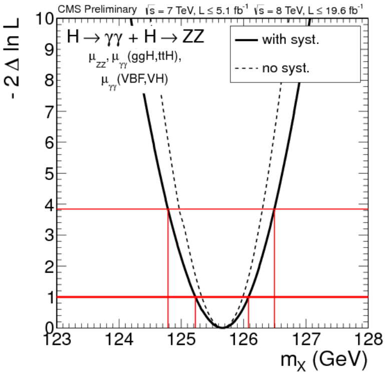
see also R.Erbacher's talk for the Top WG




TEVEWWG, arXiv:1305.3929

# A new era of EW precision physics: $\delta M_H^{exp} \approx 0.51\%$

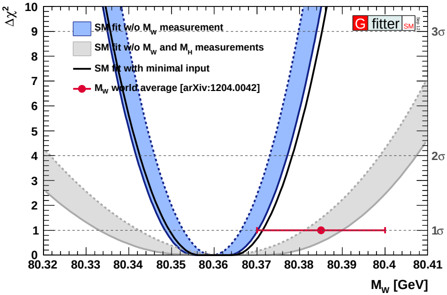


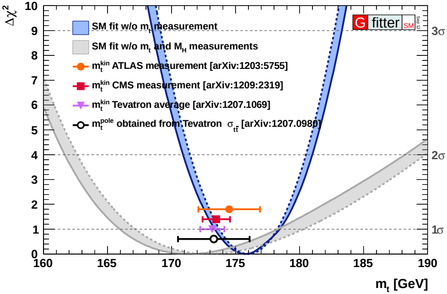




$M_H = 125.7 \pm 0.3 \pm 0.3$ GeV (CMS) CMS-PAS-HIG-13-005

$M_H = 125.5 \pm 0.2^{+0.5}_{-0.6}$ GeV (ATLAS) ATLAS-CONF-2013-014,ATLAS-CONF-2013-025

# A new era of EW precision physics: Consistency check of the SM



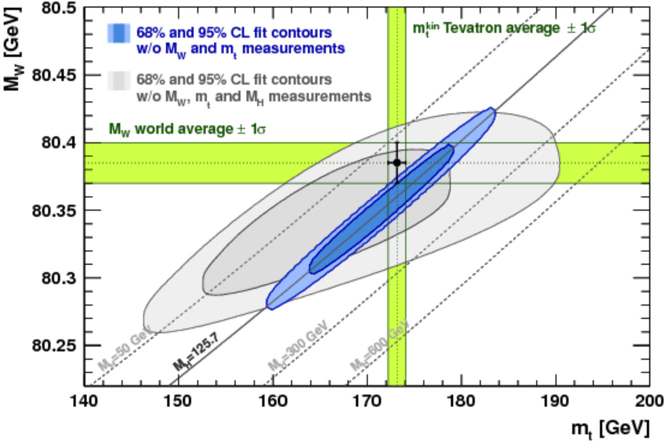




Predicted $M_{top}$ and $M_W$ before (gray band) and after (blue) $M_H$ measurement is included in the fit.

SM predictions and direct measurements agree!

Fit result: $\Delta M_W = 11$ MeV

GFITTER, arXiv:1209.2716




GFITTER, arXiv:1209.2716

# Search for indirect signals of BSM physics in EWPOs

- Consider a specific BSM model, which is predictive beyond tree-level, and calculate complete BSM loop contributions to EWPOs ($Z$ pole observables, $M_W$, ...).
  Example: MSSM
- In many new physics models, the leading BSM contributions to EWPOs are due to modifications of the gauge boson self energies which can be described by the *oblique* parameters $S$, $T$, $U$ Peskin, Takeuchi (1991):

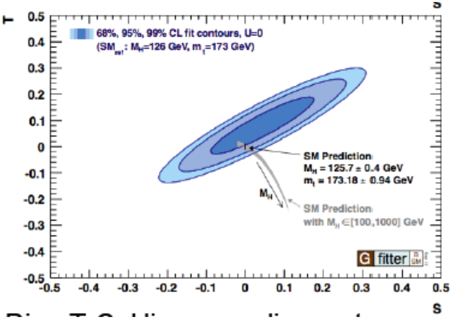
$$\Delta r \approx \Delta r^{\mathrm{SM}} + \frac{\alpha}{2 s_W^2}\Delta S - \frac{\alpha c_W^2}{s_W^2}\Delta T + \frac{s_W^2 - c_W^2}{4 s_W^4}\Delta U$$

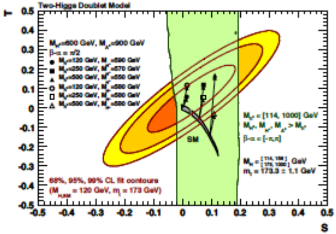
$$\sin^2\theta^l_{eff} \approx (\sin^2\theta^l_{eff})^{\mathrm{SM}} + \frac{\alpha}{4(c_W^2 - s_W^2)}\Delta S - \frac{\alpha s_W^2 c_W^2}{c_W^2 - s_W^2}\Delta T$$

- Effective field theory: Weinberg (1979); Buchmueller, Wyler (1986)
  Effective Lagrangians parametrize in a model independent way the low–energy effects of possible BSM physics with characteristic energy scale $\Lambda$. Residual new interactions among light degrees of freedom, ie the particles of mass $M << \Lambda$, can then described by higher-dimensional operators:

$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j + \ldots$$

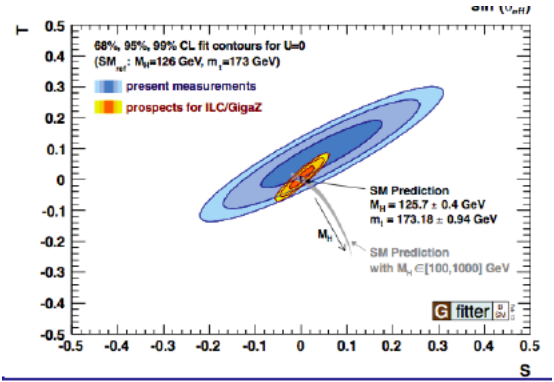
# The present: Experimental constraints on $S$, $T$ and $S$, $T$ in the 2HDM



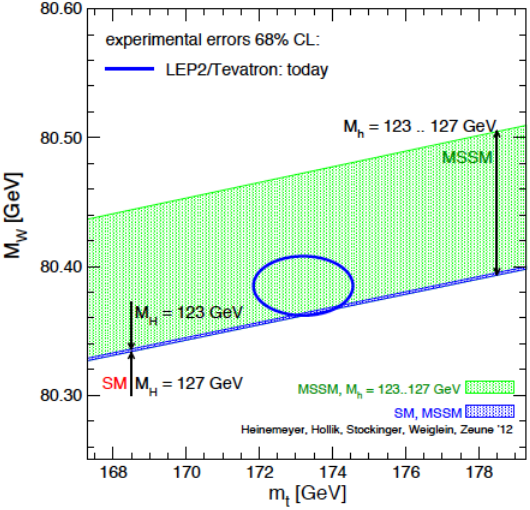

M.Baak et al, 1107.0975

# The future: Experimental constraints on $S$, $T$ from global EW fit

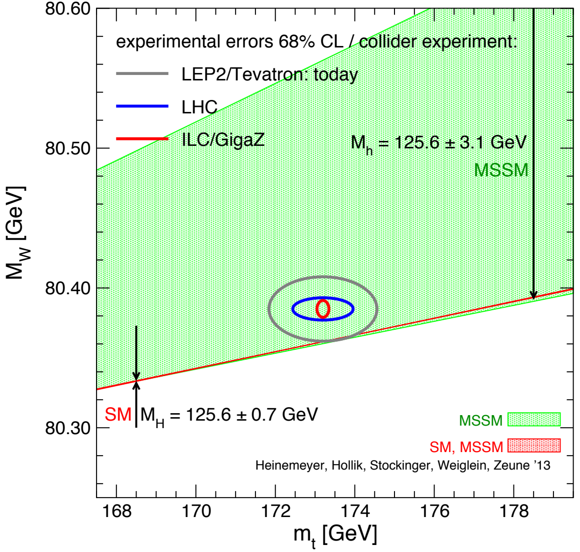



see talk by M.Baak at BNL EF Snowmass meeting

# The present: $M_W(m_{top}, M_{susy}, \ldots)$ in the MSSM

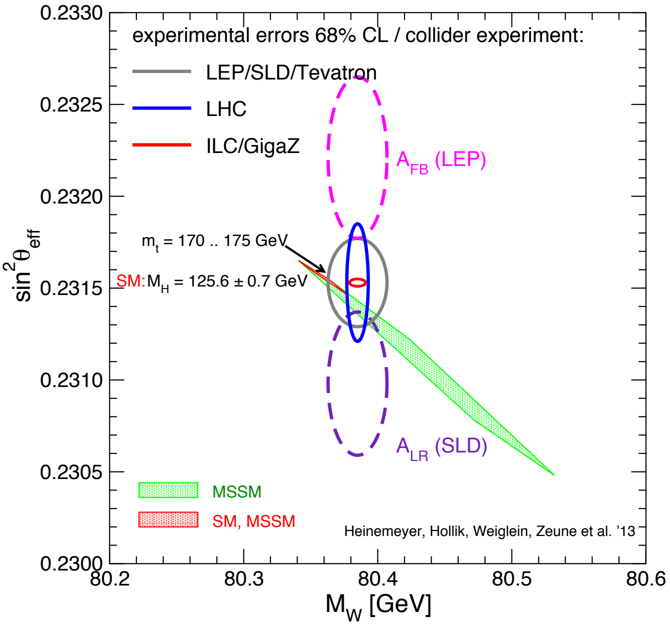


# The future: $M_W(m_{top}, M_{susy}, \ldots)$ in the MSSM




see also talk by A.Kotwal for EW WG

# The future: $M_W$ and $\sin^2\theta^l_{eff}$ within the MSSM



# The future: EWPOs and extra gauge bosons: $Z'$

$Z'$ are associated with $U(1)'$ extension:
From J.Erler's contribution to Snowmass EW WG report

- EWPOs constrain $\theta_{ZZ'}$ to $10^{-2}$ level $\rightarrow$ future precision in EWPOs will improve the constraint to $10^{-3}$ level
- In certain models, e.g. sequential $Z'_\chi$ as in GUT $SO(10)$, $M_{Z'}$ and $\theta_{ZZ'}$ are related $\rightarrow$ sensitivity of EWPOs to masses of up to $\approx 6$ TeV.
- If $Z'$ is discovered with, e.g., $M_{Z'} = 3$ TeV, EWPOs can determine size and sign of $\theta_{ZZ'}$.

From J.Reuter's talk at Seattle EF Snowmass meeting:
BSM physics could enter in the EW sector in form of very heavy resonances that leave only traces in the form of deviations in the SM couplings, ie they are not directly observable. But such deviations can be translated into higher-dimensional operators that affect triple and quartic gauge couplings in multi-boson processes:
For example, a scalar resonance $\sigma$, whose Lagrangian is given by
$(\mathbf{V} = \Sigma(D\Sigma)^\dagger, \mathbf{T} = \Sigma\tau^3\Sigma^\dagger)$

$$\mathcal{L}_\sigma = -\frac{1}{2}\left[\sigma(M_\sigma^2 + \partial^2)\sigma - g_\sigma v \mathbf{V}_\mu \mathbf{V}^\mu - h_\sigma \mathbf{T}\mathbf{V}_\mu \mathbf{T}\mathbf{V}^\mu\right]$$

leads to the effective Lagrangian after integrating out the scalar,

$$\mathcal{L}_\sigma^{\text{eff}} = \frac{v^2}{8M_\sigma^2}\left[g_\sigma \mathbf{V}_\mu \mathbf{V}^\mu + h_\sigma \mathbf{T}\mathbf{V}_\mu \mathbf{T}\mathbf{V}^\mu\right]^2$$

ie integrating out $\sigma$ generates the following anomalous quartic couplings

$$\alpha_5 = g_\sigma^2\left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_7 = 2g_\sigma h_\sigma\left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_{10} = 2h_\sigma^2\left(\frac{v^2}{8M_\sigma^2}\right)$$

# Anomalous quartic gauge couplings and heavy resonances

For strongly coupled, broad resonances, one can then translate bounds for anomalous couplings directly into those of the effective Lagrangian:

$$\alpha_5 \leq \frac{4\pi}{3}\left(\frac{v^4}{M_\sigma^4}\right) \approx \frac{0.015}{(M_\sigma \text{ in TeV})^4} \quad \Rightarrow \quad 16\pi^2\alpha_5 \leq \frac{2.42}{(M_\sigma \text{ in TeV})^4}$$

From the Snowmass EW WG report (ATLAS study):
For a different choice of operator basis:

$$\alpha_4 = \frac{f_{S0}}{\Lambda^4}\frac{v^4}{16}$$

$$\alpha_5 = \frac{f_{S1}}{\Lambda^4}\frac{v^4}{16}$$

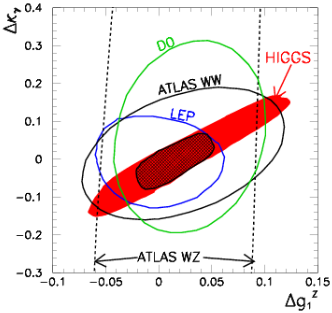
For example, $W^\pm W^\pm$ scattering at 14 TeV and 3000 $fb^{-1}$ constrains $f_{S0}/\Lambda^4$ to 0.8 $\text{TeV}^{-4}$ at 95% CL.

# A new era of EW precision physics: combined tests of gauge and Higgs interactions

$$\mathcal{L}_{eff} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$$

TGCs in terms of $f_n$ (dim6 operators):

$$\Delta\kappa_\gamma \propto (f_W + f_B) \frac{v^2}{\Lambda^2} \quad , \quad \Delta g_1^Z \propto f_W \frac{v^2}{\Lambda^2}$$




Corbett *et al.*, arXiv:1304.115 [hep-ph]

# Future of EW precision physics ?

Lesson from the LHC (so far): again the SM has proven to be very robust!

- With the discovery of the Higgs, global fits to EWPOs are now providing extremely precise predictions for $M_W$ and $\sin\theta^l_{eff}$: $\Delta M_W = 11$ MeV and $\Delta\sin^2\theta^l_{eff} = 10 \times 10^{-5}$ (compared to exp. uncertainty of 15 MeV and $16 \times 10^{-5}$).
- LHC is already providing a wealth of EW measurements at very high precision (per mil/percent level) and/or probing new kinematic regimes, and this is just the beginning.
- Further improving measurements and predictions of $W$ and $Z$ observables
  - will keep 'squeezing' the SM until we will hopefully detect a (convincing) deviation and will provide guidance to the nature of the underlying BSM physics.
  - will put more and more stringent constraints on BSM scenarios under consideration.
- When new particles are found, EWPOs can help in the identification of the BSM model and provide complementary information about the parameter space.
- The past and present tremendous experimental and theoretical efforts will have to be continued in the LHC era and even more so at future colliders to benefit from the full power and richness of EW precision physics.